

Effect of Leading edge tubercles on flow field over NACA-4415 airfoil at low Reynolds number

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Abstract

An experimental study was carried out to investigate the effect of sinusoidal leading (tubercles) on flow field over NACA-4415 airfoil at a Reynolds number of 120,000. The wave length and amplitude of the sinusoidal leading edge is 0.25c and 0.025c respectively. The global effect of sinusoidal leading edge on the flow field was assessed through pressure measurement and surf flow visualization and compared with base airfoil. The airfoil with modified leading edge shows better pressure recovery compared to the baseline airfoil. However, the inclusion of the tubercles causes spanwise flow with complex features compared to a simple 2-dimensional flow over the baseline airfoil.

1. Introduction

For the past few decades study and control of laminar separation bubble at low Reynolds number has become important for enhancement of aerodynamic performance of unmanned air vehicles. At low Reynolds number, the flow over the airfoil is initially laminar and it is prone to separate under unfavourable pressure gradient. The separated shear layer will reattach downstream of the airfoil surface after undergoing transition from laminar to turbulent state. The emerging laminar separation bubble is either long or short depending on the airfoil shape, angle of incidence, Reynolds number and freestream disturbances¹. The long bubble alters the effective shape of the airfoil and makes significant changes in the pressure distribution, yielding poor airfoil performance, whereas the short bubble act as a boundary layer trip and makes the separated shear layer reattach without significant changes in pressure distribution and airfoil performance².

Tubercles on the leading edge of humpback whale flippers, gives better maneuverability to make the sharp turn to catch the prey. Application of this kind of system living in the nature to the resembling engineering system will help to improve system operation³. Experimental study on scale model of hump whale flipper delayed the stall angle of incidence with benefit of increase in lift and reduction in drag⁴. Recent studies at low Reynolds number ($Re=180,000$) on 2D wing profiles with leading edge tubercles like the ones on hump whale flippers (Fig.1) have showed improved aerodynamic performance in terms of higher lift, lower drag and higher lift to drag ratio⁵⁻⁶. Generation of

streamwise vortices between crests of the tubercles is suggested as the possible mechanism which increases the momentum transfer within the boundary layer. This results in increase in lift and drag reduction. The prospects of using leading edge tubercles as an efficient flow control device towards controlling laminar separation bubbles at low Reynolds numbers is yet to be explored.

In the present study, influence of sinusoidal leading on the flow field over NACA-4415 airfoil was investigated through pressure measurement and surface flow visualization and compared with baseline airfoil at Reynolds number of 120,000 based on chord of 250mm and freestream velocity of 7.5m/s.



Figure 1. Humpback whales Flippers with tubercles

2. Experimental setup

2.1 The Facility and models

The experiments were carried out in the 0.55m Low Speed wind tunnel facility at the Experimental Aerodynamic Division, NAL. It is a suction type low speed wind tunnel of 0.55mx0.55m cross section having freestream turbulence of 0.15% at freestream velocity of 20m/s. A schematic of the facility is provided in Fig 1. A NACA-4415 airfoil model of chord 250mm was used in the present study. The same airfoil was modified to include leading edge tubercles in the form of sinusoidal protubances of $h/w = 0.1$ (where h is the maximum height and width of single sinusoidal proturbance). Each tubercles has the wave length of 0.25c(chord) and amplitude of 0.025c. Both the airfoils are fabricated using fibre-reinforced plastic. Measurements were carried out at Reynolds number of 120000 and angle of incidence 6°. Figures 2

and 3 shows the schematic of the facility and the airfoil models respectively.

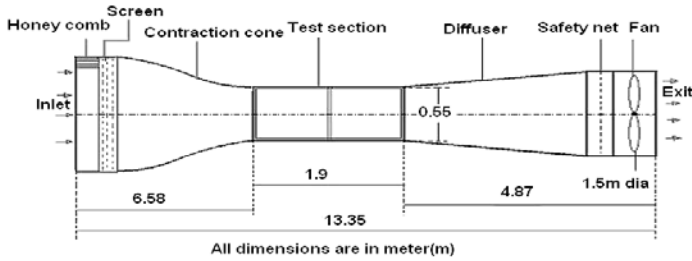


Figure 2. Schematic of the 0.55m Low Speed Wind tunnel

2.2 Steady Pressure Measurements

Steady pressure measurements were carried out on the baseline NACA-4415 airfoil with 32 ports on the upper surface and 24 ports on the lower surface using ESP scanners of $\pm 254\text{mm}$ ($\pm 10\text{-inch}$) water column range. The pressure data was acquired from a total of 56 pressure ports on the base line NACA-4415 airfoil (located along 10° inclination line to minimize flow interference from one port to the other port (Figure 3(b)). For the airfoil with leading edge tubercles, 36 pressure ports were placed along the center between the crest and trough of the tubercles as shown in Fig. with 24 pressure ports on the upper surface and 12 ports on the lower surface. This location was chosen as at this location the chord of the airfoil was same as that of the baseline airfoil. The data from the ESP scanners were obtained at 1KHz for a duration 3 sec durations and averaged at each port location. The data acquisition and recording was done using inhouse developed acquisition program using LABVIEW®.

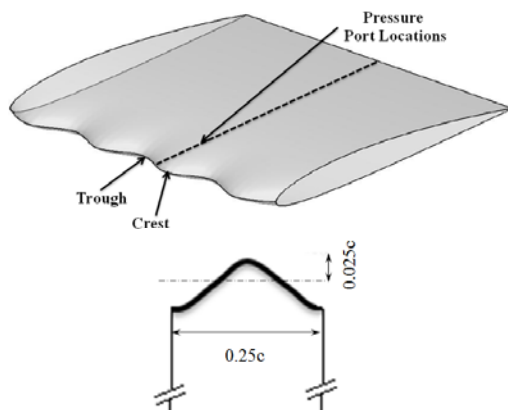


Figure 4. NACA-4415 airfoil with modified Leading Edge

2.3 Surface oil Flow

The surface flow visualization on the airfoil was carried out using a conventional oil flow visualization technique by using a mixture of oleic acid, titanium dioxide powder and SAE 60 grade vacuum pump oil in the ratio of 1:5:7. The mixture was sprayed on to the model by means of repeated flicking of the bristles of a paint brush untill the model was covered with uniformly sized, discrete dots of a size that did not move under the influence of gravity. The tunnel flow was then brought on flow condition as rapidly as possible and the streamlines then formed naturally on the surface of the model due to surface flow shear. The tunnel was run until the oil had stopped flowing and with the tunnel off, the model was photographed. The imaging was carried using a Nikon-D3X camera having a resolution of 24M pixels.

3. Results and Discussion

3.1 Pressure distribution

Surface pressure distribution on the NACA-4415 airfoil for the angle of incidences 6° at the Reynolds number of 120000 is shown in Fig .5. The flow on the upper surface accelerates and after reaching a peak coefficient of $C_p = -1.5$, decelerates. The laminar boundary layer developing on the upper surface under the deceleration (which is causing the adverse pressure gradient) observed to separate at around 35%c(chord). The constant pressure pressure in the C_p (coefficient of pressure) distribution is an indicative of the separation of laminar boundary layer in the form of shear layer and subsequent reattachment to the surface. As shown in Fig 5., the length of the separation bubble is observed to be about 30% chord (as reattachment is occurring at 65%).

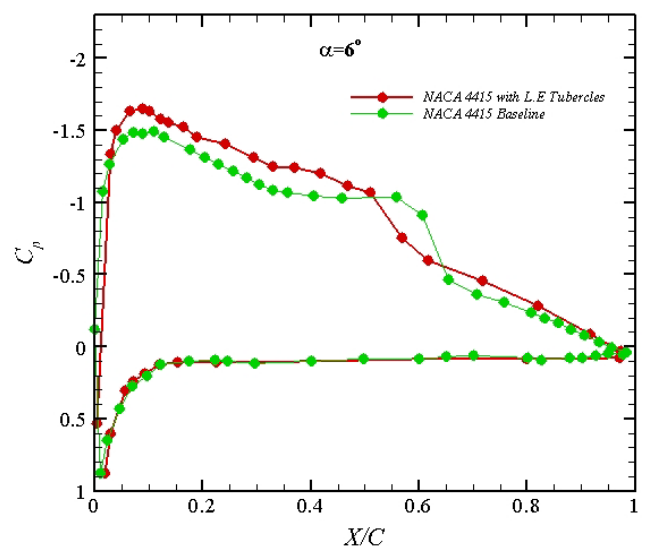


Figure 5. Pressure distribution on the NACA 4415

Pressure measurements with the tubercles show significant improvement in the pressure distribution.

Compared to the baseline airfoil, there is appreciable increase in the suction pressure. However, the airfoil with leading edge tubercles show a better pressure recovery and a constant pressure plateau is not observed as in case of the baseline airfoil. The modified airfoil with tubercles exhibits a higher C_p on the upper surface until an x/c of around 0.5. However, after $x/c = 0.5$ there is a reduction in C_p and pressure is about the same as that of the baseline airfoil. As expected the lower surface of the airfoil shows no considerable change in C_p as compared to the baseline airfoil. The absence of a constant pressure region on the upper surface implies a reduced or an eliminated laminar separation bubble. Determination of the extent of the changes to the separation bubble can only be achieved by carrying out pressure measurements along the span for the modified airfoil. This will involve rows of pressure ports along the span. On the other hand a better understanding of the nature of the flow on the airfoil can be achieved by carrying out oil flow visualization on the upper surface of the airfoil.

3.2 Surface oil flow visualisation

Surface oil flow pattern over the surface of the NACA-4415 base line airfoil at angle of incidence of 6° is shown in figure.6. For ease of understanding a marking at every one tenths of the chord was made starting from the leading edge. The oil flow visualization was carried out near one end of the span of the airfoil so as not to contaminate the pressure ports. The onset of separation, dead air region, reverse flow region can be clearly seen in the base line airfoil. The occurrence of these features collaborate well with the observations from pressure measurements. It can be seen that the the location extent of the separation bubble capture oil flow vizualition records correlates with the results obtained from pressure .

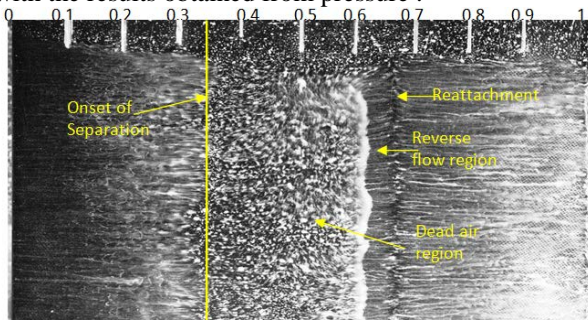


Figure 6. Flow pattern on NACA- 4415 airfoil

Figure 7 shows the flow pattern on the NACA-4415 airfoil with leading edge tubercles. It is observed that the flow pattern observed is highly in contrast to the one obtained on the baseline airfoil. Unlike the baseline airfoil, as expected, the separation line is not straight. Rather it is curved and is sinusoidal like that of the Leading edge. As reported by Johari et al⁵ this is due to the fact that the flow separation happens early in the trough region while it is delayed in the crest region. The trough portion of the airfoil has higher

leading edge curvature (smaller radius) leading to higher pressure gradient. This in turn causes the flow to separate earlier. Whereas the crest portion of the airfoil results in the flow separating further downstream.

The above mentioned nature of the flow development due to the combined effect of the crest and trough causes a reduction in dead air region. However, this dead air region varies in a carotid in shape. Due to this the flow downstream and the reattachment further is also wavy. Downstream of the dead air region we see vortex-like foot prints. This is due to the span wise entrainment of the nearby accelerated flow downstream of the crest towards the dead air region formed downstream of the trough (due to the earlier separation). Sinusoidal reattachment line corresponding to the peak and trough of the airfoil is observed.

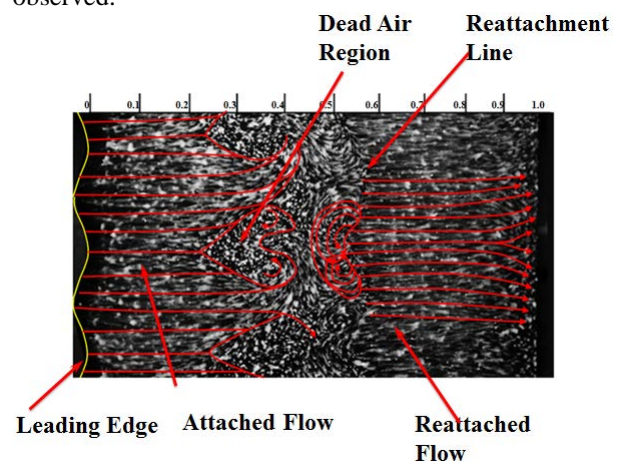


Figure 7. Flow pattern on NACA- 4415 airfoil with leading edge tubercles

4. Conclusion

The effect of leading edge tubercles on controlling the location and extent of a laminar separation bubble is investigated experimentally. The results show that the significant increase in suction pressure is obtained for the modified airfoil. An increase in pressure downstream of the suction peak is also noticed improving the efficiency of the airfoil. The studies show that tubercles are effective in reducing the extent of the separation bubble. However, it also introduces spanwise flow features. A clear understanding of these flow patterns can only be brought out by detailed, quantitative studies with techniques like Particle Image Velocimetry, which are being planned in the future.

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